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Keeping global climate change within 1.5 °C through net negative electric cities

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The development of net negative electric cities encompasses the three strategies of decarbonizing power supply, energy efficiency and electrification. There is potential to pursue these combined strategies rapidly to hold climate change to within 1.5 °C. Recent work has identified many cities in developing countries that are ideal for electrification today based on carbon intensity and high access to electricity. Net negative electric cities could be achieved by following a comprehensive policy framework for low carbon investment.

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Introduction

Many scenarios for deep decarbonization at the global scale rely on a combination of three interlinked strategies [1–3]:

1. Decarbonize power supply (i.e., eliminate the use of fossil fuels in electricity generation).
2. Increase energy efficiency (i.e., reduce energy demand).
3. Electrification (i.e., substitute electricity for fossil fuel use in engines, furnaces, among others)

As cities are seen as key actors or venues for pursuing deep cuts to greenhouse gas emissions [4–7], then clearly pursuit of the three above strategies in cities and urban areas more generally will be essential for restricting climate change to within 1.5 °C. Drawing upon results from integrated assessment models (IAMs), there will need to be a transition to *net negative electric cities*, that is, *cities that sequester more carbon than they emit in total, through provision of electricity with negative carbon intensity (t CO2e/GWh).* Cities need to pursue heightened energy efficiency and electrification, while being supplied by power that by the second half of the century has negative emissions. In this paper, we review the case for transitioning to net negative electric cities — encompassing all three strategies — including assessment of progress and potential for electrification in developing countries. We close with brief comments on policies required to achieve net negative electric cities.

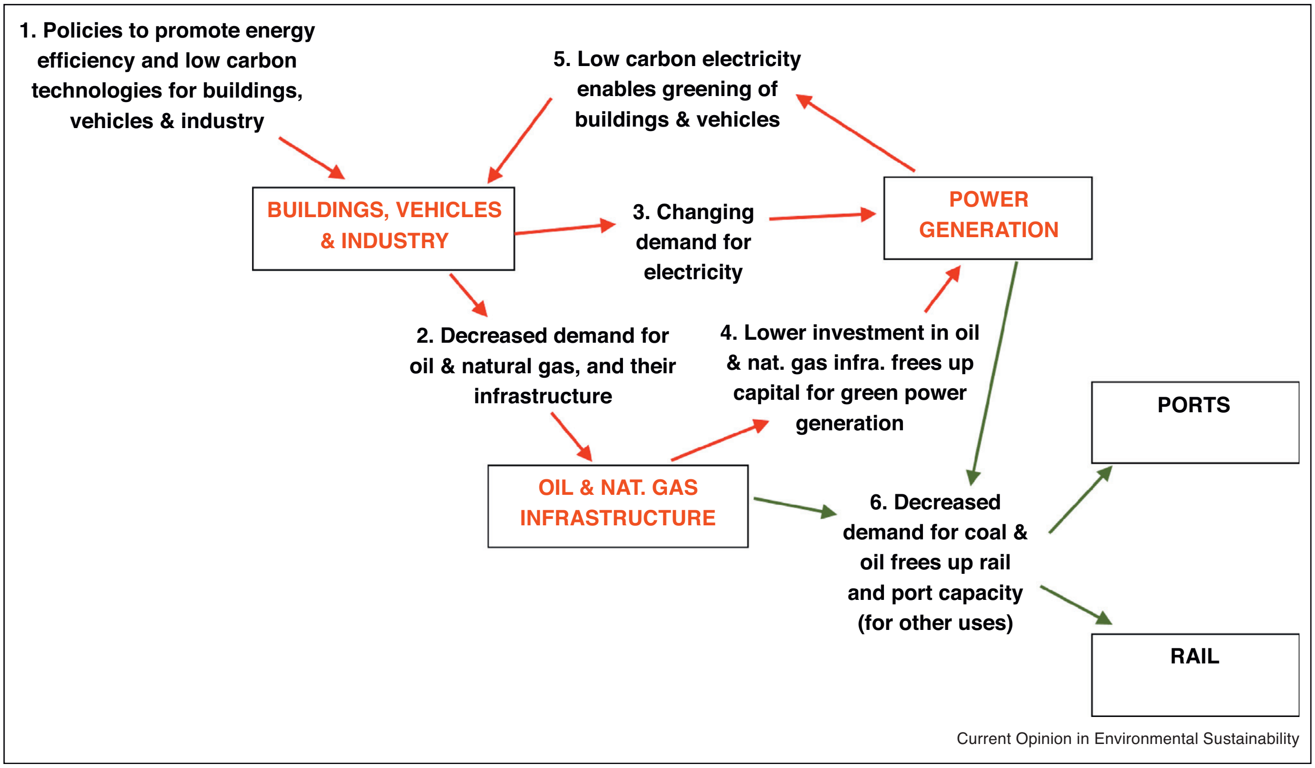
Why electric cities?

Our arguments for advocating net negative electric cities are informed by results from integrated assessment models (IAMs), but subject to some caveats. In the IPCC's AR5, the IAM scenarios with the deepest emissions cuts, within a 2 °C ceiling, were based on the three key strategies (decarbonization, electrification and efficiency). IAM scenarios falling within the 1.5 °C ceiling, reviewed by Rogelj *et al.* [8••], are different from the 2 °C scenarios in the following ways:

- Extra focus must be put on reducing CO_2 emissions (since opportunities for non-CO_2 will already be exhausted).
- Net zero carbon emissions should be reached by approximately 2045–60, and net removal of CO_2 should occur in the second half of the century.
- Energy efficiency is important; global energy demand should not grow by more than ~40%.
- Profound near-term decarbonization of energy supply is critical.

Although IAMs are possibly the best currently available scenario tools for guiding policy, they do have limitations. Review of the five most widely used IAMs noted that: some do not have macroeconomic budget closure; there is lack of physical linkages between capital stocks and material flows to build up stocks; and weak coverage of material recycling [9•]. The lack of coupling between material flows and capital investment in IAMs renders them unable to adequately represent key interactions

Figure 1



Key financial and physical interactions between infrastructure sectors contributing low carbon economic growth.
Source: Adapted from Figure 8 in Kennedy and Corfee-Morlot, 2013 [10].

between infrastructure sectors under low carbon growth (Figure 1). With decarbonization, not only can capital be diverted away from fossil fuel infrastructure towards green power generation, but large savings in future marine port and rail infrastructure costs could be achieved as fossil fuels no longer need to be transported [10]. This means that IAMs likely substantially overestimate the costs of a low carbon transition using electrification and decarbonization.

Also pertinent is that none of the five IAMs reviewed recognize consumption patterns associated with cities [9•]. This means that the IAMs miss strong linkages between urbanization and electricity consumption [11], correlation between global energy use and urban population [12], and non-linear scaling laws observed for GDP, energy use, and waste produced by cities [13,14•]. From our studies of GHG emissions for cities [15], we also note that city inventories are generally dominated by CO_2 emitting sectors: electricity, transportation, and direct building and industrial energy use (Figure S1). As city inventories are more heavily weighted with CO_2 emissions — especially due to transportation — they must play a heightened role in keeping temperatures below 1.5 °C, rather than 2 °C (following Rogelj *et al.* [8••] above).

Turning again to the three key strategies above, further observations can be made that further reinforce the necessity of developing net negative electric cities. Strategy 1, decarbonization of power supply, will be necessary under all broad approaches to climate change mitigation. Plans and roadmaps for how this can be achieved at the national scale have been developed for China [16•], the United States [17], and other countries, as well as globally. Although some questions over the feasibility of 100% renewable-electricity systems remain (e.g., reliably meeting in-time demands, providing electrical frequency, and resilience) [18], technological developments are already on the way to meet the challenging goal of decarbonizing the power supply. Cities are experimenting with ways to decarbonize power, over a range of different ownership and business models [19–21]. Achieving this goal is on the top of the agenda of many global actors, which have already put in place significant efforts to be carbon neutral by 2050.

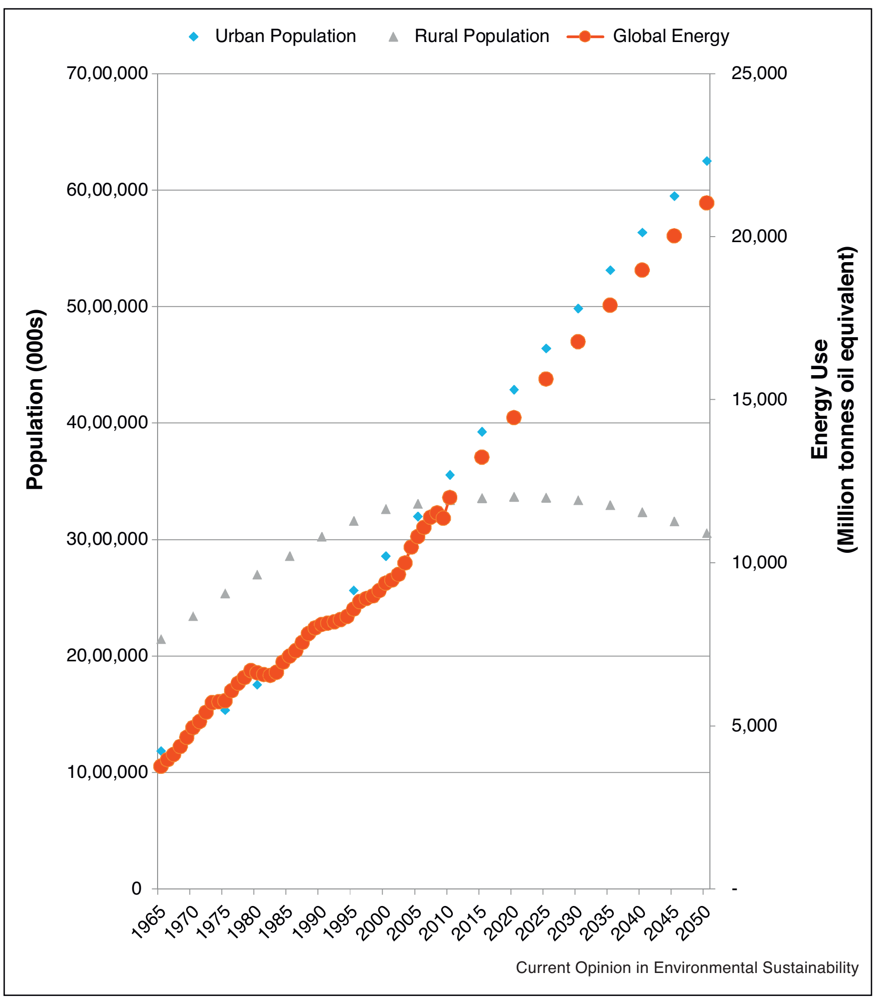
The expectation that there be net negative CO_2 emissions in the second half of the century would mean going beyond carbon neutral electricity systems, generating net negative electricity such as from bio-energy with carbon capture and storage (BECCS). The future net negative electric city could be served by power lines from biomass

power plants located at sites with sustainable forestry and suitable geological conditions for CO_2 storage. Another option might be to have biomass combined heat and power with district heating in cities, but this would require piping CO_2 out to suitable storage sites, as well as shipping biomass in. There are concerns, however, that widespread use of bioenergy would threaten food security through competing for land [22].

The second strategy — increased energy efficiency — is also essential. There is tremendous potential to improve energy efficiency across all sectors of our economies. Globally, it is estimated that about 70% of the world's energy use takes place outside of any efficiency performance requirements. The potential physical energy efficiency of many engines, heaters, appliances, devices, and systems is revealed through second-law efficiencies. A global review found that energy demands could be reduced by ~90% if energy conversion devices were operated at their theoretical maximum efficiency, with savings of over 50% achievable using current technologies [23]. Energy efficiency has to be increased at all stages of the energy chain, from generation to final consumption. At the same time, the benefits of energy efficiency must outweigh the costs, for instance those that result from carrying out renovations. Despite the significant efforts put in place in the recent years, much more can be done to improve energy efficiency in urban environments.

A possible concern with respect to the 1.5 °C ceiling is whether or not energy efficiency measures could hold increases in global energy use to no more than 40% over the 21st century, as suggested by Rogelj *et al.* [8••]. There is a clear relation between global energy

Figure 2



Note: The urban access to electricity data are for 2012. The carbon intensity of the national electric grid data are the average from 2011 to 2013.

Global energy use, urban and rural population, 1965–2010 (from Figure 3 in Bristow and Kennedy, 2015 [12]), with projections to 2050. (Population data from UN Statistics; energy data from IEA.)

use and urbanization that is consistent with the thermodynamic idea that cities are dissipative structures [11,24] (which may be interpreted as a wealth effect). Global energy use grows not only with increasing energy use in cities, but in upstream life-cycle energy use associated with goods and materials consumed in cities. Based on the UN's medium projections for urbanization by 2050, and the statistical model of [11], global energy use can be expected to approximately double by mid-century (Figure 2). If energy efficiency measures are unable to curb this growth, then we need a hedge against a possible doubling of global energy use. The hedge can come from additional emphasis on electrification with decarbonization of electricity.

Electrification — strategy 3 — entails substituting electricity for fossil fuels used in engines, furnaces, among others. There are several approaches to electrification, including the replacement of internal combustion engines with electric vehicles (EVs), and natural gas furnaces with heat pumps (Table 1). Some segments of urban energy use — especially heating of buildings — can be made carbon neutral without requiring electricity, using technologies such as solar water heaters, passive building design, or biomass district heating, for example. These approaches should certainly be encouraged, but they do not cover all sectors. Moreover, a particular advantage of electrification is the potential for it to be done quickly, meeting the urgency expressed by Rogelj *et al.* [8••]. For example, simulations of transition to low carbon cities using realistic technology diffusion curves [25,26] suggest that long periods of several decades would be required to retrofit existing building envelopes. Although such retrofitting should be pursued, the quicker action is to replace home furnaces and heating systems with electrically powered air or ground-source heat pumps.

Similar arguments can be made for electric vehicles, which are rapidly increasing in market scale [27•], and may continue to do so as battery prices decline [27•,28]. Market share for EVs reached 23% of new car sales in Norway and 10% in the Netherlands in 2015 [27•]. Even with current technology, close to 90% of all personal vehicle transportation miles in the United States could be met using EVs [29•]. Although very ambitious, a high market penetration of EVs as foreseen in 2 °C scenarios is comparable with other significant market transformations in powertrain technologies that took place in the recent past, such as the spread of diesel technology in Europe starting from 1990, and the hybridization of the Japanese vehicle fleet [27•].

Table 1

Examples of technologies for electrification.

Fuel based technology	Electric equivalent or replacement
Automobile with internal combustion engine	Electric vehicle (EV)
Diesel buses	Electric buses or streetcars
LPG or diesel-powered rickshaws	Electric rickshaw
Short-haul air flights	High speed electric trains
Natural gas or oil furnaces	Ground or air source heat pumps
Charcoal, biomass, propane, LPG, natural gas or other fossil fuel stoves	Electric stoves or cook stoves
Kerosene, paraffin or other fossil fuel lanterns	Solar lanterns of electric/LED lighting

Progress towards electric cities

Over the past two decades there have been various real developments, typically at the neighbourhood or community scale, which embrace the ideals of the net negative electric city, or other variants of the 'solar city' [30,31]. Although still only a small collection of buildings, Masdar City in the United Arab Emirates is the world's only city powered entirely by the sun, with integrated technologies such as EVs, PV plants, wind farms, and geothermal heat pumps [32]. Masdar is an exceptional case because the city was built from the ground up with the very purpose of being solar powered. In Australia, Adelaide became that country's first official 'solar city' in 2007, following a public–private initiative that put solar technology at the centre of a national strategy for sustainable urban development [33]. Adelaide has installed hundreds of solar-powered buses, buildings, and street lights throughout the city. In Freiburg, Germany, the municipal council has adopted long-term energy policies, guidelines, and technologies to enable that city to become Europe's most prominent solar region [34]. Chinese cities are also striving for solar city status: Rizhao (meaning 'city of sunshine') is leading this movement with city-wide integration of solar-powered street lamps, traffic signals, and cooking facilities [35]. In Africa, many towns and villages are already powered by solar electricity. Rema, Ethiopia, is the largest 'solar village' in East Africa, with two thousand homes powered by PV cells [36].

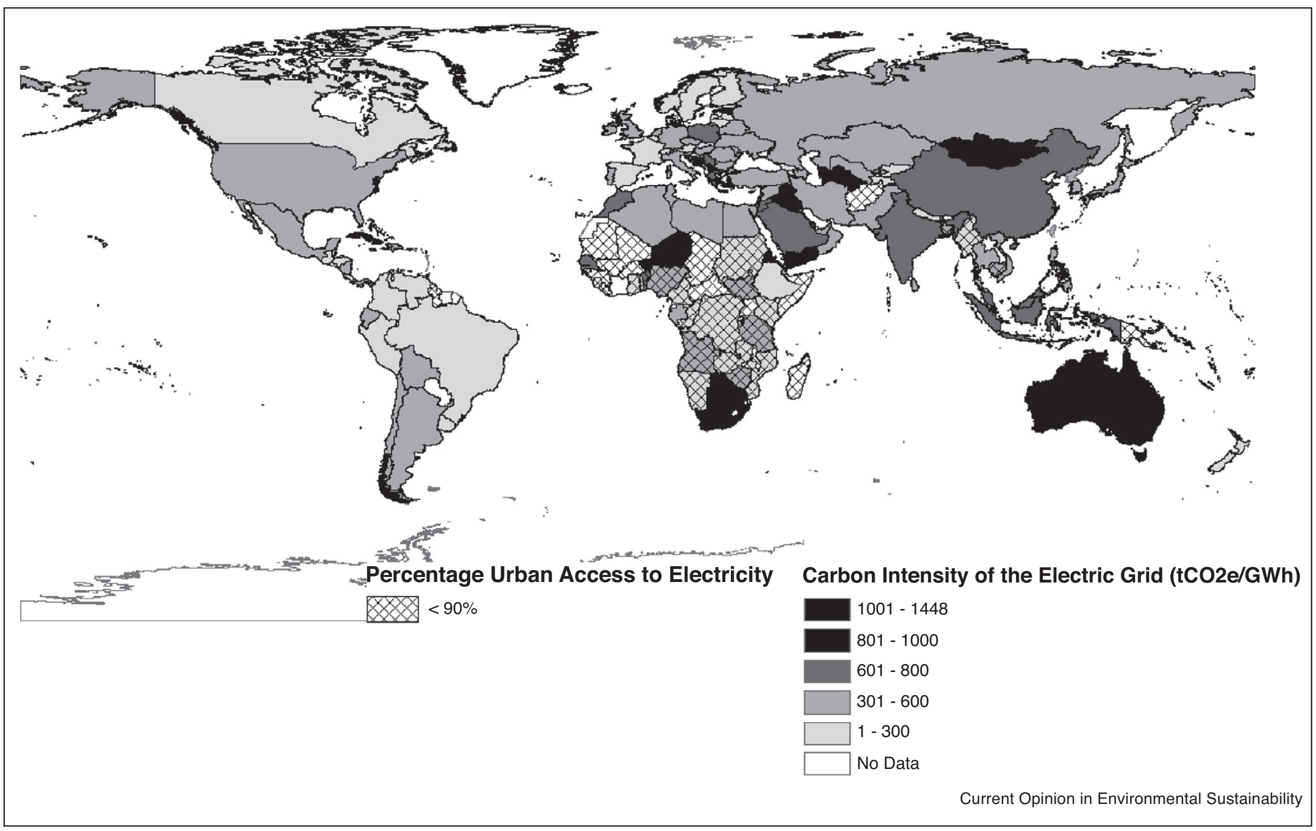
The potential to create more electric cities has increased with the declining cost of renewable energy, both utility-scale and distributed. Between 2009 and 2014, the cost of solar photovoltaic (PV) modules declined three-quarters, while the cost of wind turbines declined by almost a third [37]. In 2015, the globally weighted average levelized cost of electricity (LCOE) for onshore wind was \$60/MWh, which is comparable to the costs for fossil-fuel generation of between \$45/MWh and \$140/MWh. Between 2010 and 2015, the LCOE of utility-scale solar PV fell by 60%. During 2016, tenders for utility-scale solar in Dubai (\$30/MWh), Peru (\$50/MWh) and Mexico (\$27/MWh), and wind in Morocco (\$28/MWh), Mexico (\$32/MWh) and Chile (\$29/MWh), all indicate the further decline in costs and the competitiveness with fossil fuels [38]. The IEA

estimates the global technical potential of rooftop solar PV to be 9100 TWh, which could supply 30% of the electricity needs of cities in 2050 [39]. Continued decline in the costs of renewables also impacts the choice between grid extension and distributed solar homes [40•].

Progress towards net negative electric cities can be measured using two parameters: the share of end-use energy supplied by electricity and the carbon intensity of the electricity (Figure S2). Analysis of the progress of the world's 27 megacities towards low carbon electric cities found that Paris, Rio de Janeiro, and Sao Paulo are most advanced, sourcing approximately one-third of their end-use energy from low carbon electricity [21,41]. Indian megacities have relatively high use of electricity as a percentage of total energy use, excluding informal settlements, but it is carbon intensive. Amongst the wealthier megacities, the highest levels of electricity in total end-use energy occur in Osaka (39%) and Tokyo (34%).

Given the need to act quickly to reduce emissions, a strategic consideration is whether or not electrification should be pursued today in cities where electricity supply has yet to be decarbonized. Examination of life-cycle studies of ground-source heat pumps, electric cars, vans, heavy trucks, passenger trains, and freight trains [2,7,42•] has identified an approximate key threshold of 600 t CO2e/GWh for the carbon intensity of electricity. Below this value (+/−∼100 t CO2e/GWh) life-cycle GHG emissions will generally be reduced when substituting fossil fuel engines and furnaces with electrical equivalents. Based on the carbon intensity of national power supplies, Figure 3 shows that many countries are already below the 600 t CO2e/GWh threshold and so will generally reduce emissions when pursuing electrification today. For example, the average carbon intensity in Europe in 2014 was 331 t CO2/GWh; hence, a standard EV consuming 15 kWh per 100 km emits 50 g CO_2/km, which is well below the 2021 EU target of 95 g CO_2/km for new cars [43]. To meet the 1.5 °C ceiling, however,

Figure 3



Urban access to electricity and average carbon intensity (t CO2e/GWh) of national electric grids (2011–2013). Cities in light shaded countries (below 600 t CO2e/GWh) can typically reduce life-cycle GHG emissions through electrification at current carbon intensities, though carbon intensities will vary by states/provinces/regions within countries. *Note*: The urban access to electricity data are for 2012. The carbon intensity of the national electric grid data are the average from 2011 to 2013.
Source: Adapted from Figure 2 in Kennedy *et al*., 2017 [44].

city power supplies must rapidly decline, eventually to below 0 t CO2e/GWh.

Potential for electrification in developing countries

As much of the urbanization this century will occur in developing countries, the transition to electric cities is particularly important in cities of Africa, Asia and South America. We identified some candidate cities in developing countries that are ideal for electrification today based on: (i) carbon intensity being below the 600 t CO2e/GWh threshold; and (ii) access to electricity already being high (>90%) so that electrification of fossil fuel devices does not exasperate inequities in access [44]. Based on these factors electrification is a good strategy to pursue in all South American cities, many cities in the MENA region (e.g., Algiers, Cairo, Karachi, Tehran, Tunis) and a few in Asia (e.g., Bangkok, Ho Chi Minh, Kathmandu, Manila, Yangon; see Table S1).

Many cities in developing countries rely on diesel generation, especially for back-up power, but distributed renewables have the potential to diminish the role of diesel. For example, the LCOE for stand-alone, off-grid PV systems in Nigerian cities (Lagos, Kano, and Onitsha) is now in the range of $0.2–0.5/kWh, including battery costs, which is lower than the values for diesel generation [45]. Likewise, in Somaliland, an analysis of a hybrid PV-wind-diesel system in the state's largest city, Hargeisa, found that the cost of energy to be 70% less than that of a diesel-only system, with operating costs reduced by 43% [46].

As costs continue to decline, development of electric cities can also begin to address huge challenges of access to energy in informal settlements. As UN-Habitat [47] notes, about 1 billion people live in slums and lack access to basic infrastructure services (energy, water, sanitation, among others). Many residents in slums rely on less efficient (and more polluting) fuels in the energy ladder for cooking, heating, and lighting [48]. Greater access to electricity in slums is therefore a suitable means to improve living standards, while reducing GHG emissions through switching to cleaner, more efficient energy supplies [49]. The main issues in electricity provision to slums are electricity theft (especially in Latin America) and lack of investments especially in Africa [50].

Achieving net negative electric cities

We close with a key question: How much progress towards net negative cities can happen autonomously — within the context of current markets — and how much will need to be induced by policy? The short answer is that all five elements of a comprehensive OECD policy framework for low carbon investment will be required: (i) Strategic policy goal setting; (ii) Enabling investment policies for competitive, open markets and green infrastructure; (iii) Financial regulations, policies, and mechanisms to attract private sector participation; (iv) Human and institutional capacity building; and (v) Promoting of green business conduct and consumer engagement [51]. The type and extent of policies will differ, however, for the three key strategies (decarbonization, electrification, and efficiency), and will also depend on national context. Energy efficiency measures, for example, are encouraged by enforcement of appropriate standards (an investment enabling policy) and consumer engagement, amongst other elements. Promotion of electrification strategies may also benefit from technical standards and consumer engagement, although the high rate of EV adoption in Norwegian and Dutch cities, for example, is related to suitable national pricing incentives, and investment in charging infrastructure. There is strong potential to develop net negative cities in developing countries, as argued above, but suitable financing environments (element 3) may still remain a barrier in the least developed countries.

Policies to encourage decarbonization of power supply are arguably ahead of those aimed at electrification. Electricity is being decarbonized today as a result of appropriate policies in the past, such as feed-in-tariffs, reverse auctions, net metering, among others. The levelized costs of renewable energy supply have declined dramatically to be competitive with fossil-fuel power generation; nonetheless, development of new pricing models — beyond feed-in-tariffs — and enhancement of technical capacities, for example, to deploy smart technologies, may be required for utilities to be more aggressively involved in the decarbonization of urban electricity grids using smart technologies [21]. Smart grid technologies enable the full deployment of distributed generation (DG) systems [52], which we consider among the main enablers of electric cities. DG is gaining importance for its resilience to natural hazards and its flexibility to integrate storage systems and intermittent renewable energy sources [53,54]. DG also opens potential for utilities to transform from network-based to service-based business models, for example, by adopting emerging technologies like blockchain [21,55].

Possibly the most important point is that the three strategies (decarbonization, electrification, and efficiency) need to be incorporated into well-coordinated, clearly communicated national climate strategies, which are aligned across government (i.e., element 1 in the policy framework above [51]). The need for coordination is particularly stressed because the three strategies simultaneously involve decreasing electricity use (efficiency), increasing electricity use (electrification), and changing the source of electricity (decarbonization). This level of integration and coordination must, moreover, play out in the multi-level governance context of cities [4].

Conflicts of interest

None.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cosust.2018.02.009.

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